High-Performance Commercial Building Systems Program

Element 2 – Project 2.1 – Task 2.1.2

Standardized Building Performance Metrics

Final Report

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October, 2002

1. Introduction

Buildings often do not perform as well in practice as expected during pre-design planning, nor as intended by design. While this statement is generally considered to be true, it is difficult to quantify the impacts and long-term implications of a building in which performance does not meet expectations. Current building design, construction, and operational practices are devoid of quantitative feedback that could be used to detect and correct problems both in an individual building and in the building process itself.

A key element in this situation is the lack of a standardized method for documenting and communicating information about the expected and actual performance of a building across its life cycle. This deficiency leads to several shortcomings in the management of building life-cycle information. Planners may not clearly specify their performance expectations. Designers cannot concisely document their design intent in response to performance expectations nor can they refer to clear documentation of overall project goals to optimize their design decisions. Commissioning personnel have no standardized method for documenting the results of performance testing. Post-occupancy building performance cannot readily be compared to expectations in an attempt to evaluate and improve design and operation decisions. Lastly, without quantification of the magnitude of performance problems it is difficult to motivate building process participants to alter their current practice.

The research reported here has been undertaken to address this situation and has the following objectives:

- Elaborate an envisioned scenario for tracking performance metrics in a manner that improves and assures actual building performance across its life cycle.
- Develop a data model for building performance metrics that is consistent with the Industry Foundation Classes (IFC) [1], developed by the International Alliance for Interoperability (IAI) [2], and is both robust and flexible enough to archive and exchange metric data in their many forms.
- Implement the data model in software to illustrate the key concepts of archiving, sharing, and tracking expected and actual building performance to better assure overall performance across the life cycle.
- Identify and define standard building energy performance metrics so that various participants can consistently interpret and apply them across the building life cycle.

- Explore related building performance frameworks that provide a larger context within which energy performance metrics fit.
- Relate this work to other ongoing research in the building performance area such as benchmarking, simulation, and software interoperability.

This report begins with a description of the concepts underlying a data model for performance metrics and its use in tracking building performance across the project life cycle. A standard data model capable of supporting these concepts is then presented. This data model has been defined within the context of a complete building description data model known as the Industry Foundation Classes (IFC) [1], developed by the International Alliance for Interoperability (IAI) [2]. Metracker, a software prototype based on this extended IFC model, is then described to illustrate the implementation and application of the data model and its underlying concepts to make them easy to understand, thereby maximizing their effectiveness.

The report then focuses on the issue of standardizing specific energy-related performance metrics that can be instantiated using the extended IFC data model. Standardized building performance metrics are required to assure that various users consistently identify and apply these metrics both within an individual project and across the diverse stock of building facilities.

A review of existing and emerging building performance frameworks provides a broader context within which energy-related performance metrics can be defined. Several such performance frameworks are discussed in this report with attention given to where energy-related metrics fit within these larger contexts.

Sets of energy-related performance metrics that have been identified by various efforts in this field are then presented in a hierarchically organized format similar to that defined in the extended IFC model. Each of these sets is a candidate for standardization, within an individual building project to support performance tracking over time, across projects that wish to make comparisons between multiple buildings, and/or in the development and use of a building performance database to support benchmarking and related procedures (e.g., setting expectations for design). Methods for instantiating these performance metric sets in Metracker are discussed.

This report concludes with a discussion of related work that further illustrates applications of this research. This discussion is also intended to identify potential avenues to making market connections for this research.

2. Life-Cycle Building Performance Metric Tracking

A building project begins with a consideration of the various performance objectives of interest to building stakeholders (e.g., owners, designers, operators, occupants, etc.). While primary attention is generally given to space requirements and construction costs, a wide spectrum of objectives may be at least informally considered at this stage, including: energy-efficiency; environmental impact; life-cycle economics; occupant health, comfort and productivity; and building functionality, adaptability, durability, and sustainability. The process of elaborating the objectives for a given building project is often referred to as programming. The intent of programming is to define the desired performance for a facility so that design and operations decisions can be made to achieve this performance. The outcome of programming is most commonly recorded in freeform text that becomes part of design and construction documentation. This documentation may be frequently referenced during design, and occasionally referenced during construction, but then most often is lost from that time forward.

Performance metrics can be used to more clearly and quantitatively define the performance objectives for a building. Documenting and communicating performance metric data can provide value across the complete life cycle of a building project, from planning, through design and construction, into occupancy and operation.

2.1. Performance Metrics

Performance metrics, as defined here, are intended to explicitly represent the performance objectives for a building project, using quantitative criteria, in a dynamic, structured format. One or more metrics may be identified for any given performance objective that building process participants wish to specify and track. A guiding principle in selecting a performance metric is to identify a critical variable that measures, reflects, or significantly influences a particular performance objective. To be useful across the building project life cycle, each metric must also be capable of being either predicted or measured at various stages of the project so that the achievement of the associated objective can be evaluated.

For example, a high-level performance objective may initially be identified using only a qualitative statement such as the desire to "optimize energy performance" in a building. In order to assure the achievement of an objective statement like this, it is helpful to elaborate it using multiple metrics that influence its overall satisfaction. This elaboration can be organized hierarchically. The hierarchy in Figure 1 shows one possible subset of performance metrics that could be used to specify, track, and maintain energy-efficiency in a building. Note that each performance metric is not necessarily a simple arithmetic sum of its constituent metrics. For example, while Whole Building Energy Use is the sum of its primary energy end-uses, Cooling System Energy Use is influenced by a variety of factors including Chiller Efficiency and Cooling Load, among other possible elements.

- Optimize Energy Performance
  - Whole Building Energy Use
    - Cooling System Energy Use
      - Chiller Efficiency
      - Cooling Load
    - Heating System Energy Use
    - Lighting System Energy Use
    - Ventilation System Energy Use
    - Equipment Energy Use

Figure 1. Performance metric breakdown for energy performance.

Performance metrics come in a variety of forms for which there is presently little standardization. For example, chiller efficiency can be specified in numerous ways including a single value parameter like coefficient of performance (COP), multiple data points representing a two-dimensional part load curve for specific operating conditions, a three-dimensional part load surface across the full operating regime, or a mathematical curve or surface function representing these same data.

Moreover, the preferred method for documenting a performance metric may change over the life cycle of a project. Using the chiller efficiency example, pre-design planning might specify a desired chiller COP. Detailed design simulation might employ a mathematical representation (e.g., a curve fit) of the performance of a generic chiller type. In-situ measurements taken during commissioning could consist of a series of data points across the operational range of a newly installed chiller. Performance during the operations and maintenance (O&M) phase would likely be comprised of time-series data collected during normal operation. The data model specification of a performance metric must be flexible enough to accommodate this variety of forms. The details of the data model specifications for performance objectives and metrics are given below.

2.2. Life-Cycle Performance Tracking

The performance objectives for a building, and their constituent metrics, often change as a project moves through time. Objectives become more fully elaborated and are modified as conflicts are discovered and resolved. Similarly, additional performance metrics may be identified, their desired performance levels (benchmarks) may change, and the actual performance of a building will vary over time. A data model for tracking performance metrics must therefore be capable of archiving a history of these changes across the life cycle of a building.

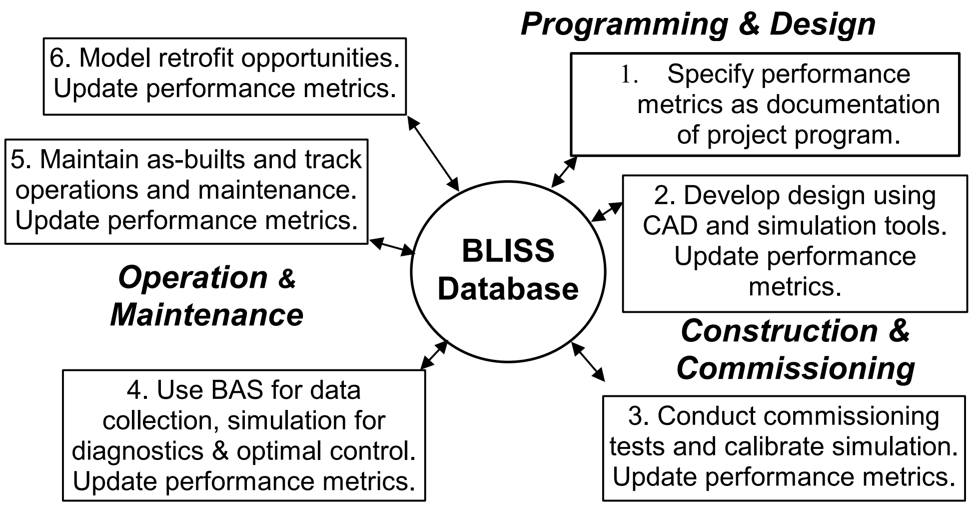

Figure 2. Life-cycle performance metric tracking scenario.

Figure 2 illustrates a scenario for tracking performance metric data across the life cycle of a building. The scenario begins during pre-design planning where an initial set of performance metrics are specified as documentation of the building program. During design, this initial set is elaborated and modified as the design evolves. The results of simulation and other assessment methods are used to update the performance metric data. These assessment results become the benchmarks of expected performance for the final building design. Carried forward to the commissioning phase, these design benchmarks identify both what to measure in the constructed building, and the expected level of performance with respect to each metric. Following commissioning the updated metric data act as as-built benchmarks for use during ongoing operations, maintenance, and retrofit of the facility. Periodic assessment of ongoing performance can then be performed by comparing these benchmarks to data collected by a building automation system (BAS).

This continually updated archive of performance metric data thus serves to support numerous activities across the life cycle. The accumulated archive of data additionally captures a performance history of the project that can be analyzed to evaluate the success of various decisions along the way, leading to an overall improvement in the delivery and maintenance of the built environment.

3. IAI/IFC Performance Metric Data Model

The concepts and details of performance metric tracking discussed in the previous section have been incorporated into a data model within the Industry Foundation Classes (IFC) [1]. The IFC data model specification has been developed by the International Alliance for Interoperability (IAI) [2] to promote the seamless exchange of data between software tools used by participants across the life cycle of a building.

3.1. IAI/IFC Overview

The mission of the IAI is "to provide a universal basis for process improvement and information sharing in the construction and facilities management industries" [3]. The IAI is currently organized into nine regional entities representing an international alliance of participants from widely diverse constituencies, including architects, engineers, contractors, building owners, building product manufacturers, facility managers, research scientists, software vendors, government officials, and academics.

The intent of the IAI is to specify how the elements that occur in a constructed facility (including tangible elements such as walls and ducts, and abstract elements such as space, participant, and process) should be represented electronically. These specifications constitute what is commonly referred to as an object-oriented data model, useful in sharing data between different software applications. The object-oriented data model that the IAI continues to develop is called the Industry Foundation Classes (IFC). To date, there have been several official releases of the evolving IFC model, identified successively as IFC R1.0, IFC R1.5, IFC R1.5.1, IFC R2.0, and most recently IFC 2x.

Software developers did not seriously begin implementing IFC data import and export capabilities into their software tools until IFC R1.5.1 became available. At this time there are over twenty software implementations based on IFC R1.5.1, with over ten of these tools available to the public. Over twenty-five tools have been implemented based on IFC R2.0 (some duplicates with IFC R1.5.1). Of these tools, eighteen have been officially certified by the IAI as being compliant with either IFC R1.5.1 or R2.0. The developers of over fifteen of these tools have publicly stated their intention to implement the latest IFC 2x version in the future. For up-to-date information on implementation activities, visit the IAI Implementation Support Group website [4].

This is not to say that the IFC import/export capabilities of these software tools are completely robust and ready for use in actual building projects. There are still numerous issues and technical problems to be worked out before the goal of seamless data sharing is achieved. However, the implementation efforts to date represent a considerable investment in IFC technology by software vendors, and indicate a serious commitment to bring this technology to market.

The IFC data model ideally includes the specifications for every class of building element that is required to support data sharing between all software tools used by building professionals. This is a difficult long-term goal that has not yet been achieved. However, the versions of the IFC model that have been released to date do capture a significant portion of a complete building data model.

In addition to the limitations that still exist in the IFC model, all software tool implementations to date have further reduced the scope of the model that they support. It is common practice to only implement import/export capabilities for that portion of the IFC model that is relevant to the primary end users of a tool, or related set of tools. This is referred to as implementing a focused "view," or subset of the model. The early IFC implementations have been done by vendors of computer aided drafting (CAD) tools. For this reason the initial focus of these implementations has been on the geometric representation of tangible building elements such as walls, windows, and doors that has been dubbed the "CAD view" of the IFC model. While the CAD view is certainly an important portion of the overall IFC model, a more complete view of the model is needed to support the life-cycle performance metric tracking scenario described above.

3.2. Building Data Model with Performance Metrics

The R2.0 and 2x versions of the IFC data model include specifications for classes that represent performance metrics for buildings. Figure 3 shows a high-level conceptual diagram of an IFC data file based on these data models. One part of this conceptual diagram is a detailed description of the components and systems contained within a building, such as walls, windows, spaces, and HVAC and lighting equipment. The complete set of these components and systems are aggregated into what is referred to here as a Product Model, as shown on the right of this figure. The left of the diagram represents a set of performance objectives and metrics, as discussed in Section 2.1, that are aggregated into what is referred to here as a Performance Model. The Product and Performance Models for a specific building are combined into a single IFC data file for archival and sharing.

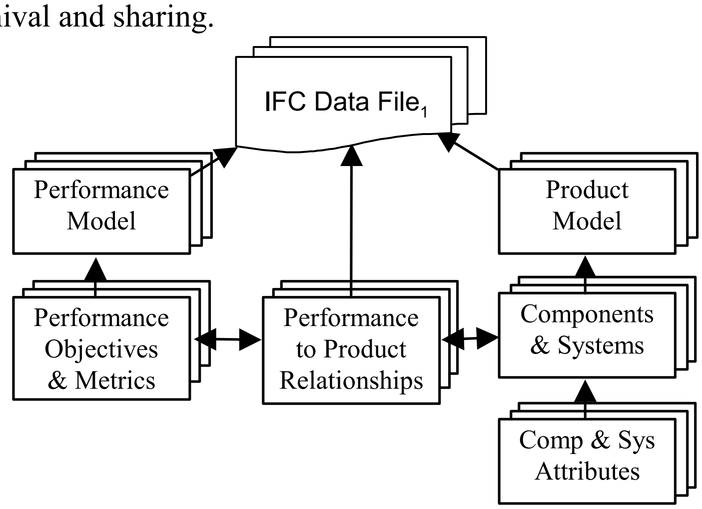

Figure 3. Conceptual model of IFC with performance elements.

The box in the middle of Figure 3 represents a set of relationships between the components and systems of the Product Model, and the objectives and metrics of the Performance Model. One use of these relationships is to link archived performance data with a specific component, to track its performance over time (e.g., the expected and actual performance of an individual chiller in the facility). Another use of these relationships is to document the rationale behind design and operation decisions by capturing the relationship between performance objectives/metrics, and the components/systems selected to achieve these objectives. For example, capturing a link between a specified glazing type and a performance metric for interior daylight level, documents the rationale behind the glazing specification. This type of documentation can help reduce unexpected ramifications from altering the specification at some later point (e.g., during value engineering). Note that while the ability to represent these relationships exists in the IFC data model, this feature has not yet been implemented in the Metracker software described below.

Multiple copies of the combined IFC data file are depicted in the diagram to illustrate the archival of versions (snapshots) of the project as it moves through its life cycle (e.g., design, construction documents, as-built, as-operated, as-renovated, etc.). Each individual version is archived as an individual IFC data file. In general, each new version for a given project will be created by modifying the previously archived version.

3.3. Metracker Software Implementation

A software prototype called Metracker has been developed to demonstrate the specification, tracking, and visualization of building performance objectives and their associated metrics across the complete life cycle of a building. The underlying concept, as discussed above, is that to better assure the intended performance of a building, it is necessary to establish a baseline benchmark for expected performance and periodically compare actual performance to this baseline. This process requires a standardized yet flexible format for archiving performance data, and sharing these data between various software tools and their users across the building life cycle. Ideally, these performance data are archived with, and related to, other information about the building, as discussed in the previous section. To these ends, Metracker is based on the IFC data model described above.

3.3.1. Intent of Metracker Prototype

It should be emphasized that Metracker is fundamentally a user interface that provides a window into the underlying IFC data model and the project-specific contents of a data archive based on this model. The Metracker interface is tailored to focus attention on tracking building performance, and thus provides specific capabilities such as metric data visualization. However, the building performance data viewed through the Metracker interface are ultimately archived in one or more IFC data files that are accessible to any software cognizant of the IFC data model. This is an important distinction to keep in mind when thinking about Metracker, life-cycle performance metric tracking, and software interoperability. It is not really Metracker itself that tracks building performance, but rather the data stored within an IFC archive that track performance.

There are a number of software tools that are related to the process of tracking building performance. These tools include those that predict the design performance of buildings (e.g., energy simulation), that measure the actual performance of buildings (e.g., enhanced energy management and control systems), and that aid in the diagnosis of performance problems (e.g., performance visualization and diagnostics). However, at this time none of these tools are conceived for archiving both intended and actual performance metric data across the full life cycle, beginning in pre-design planning. Nor do these other tools archive a complete building model alongside an associated set of performance metrics as is defined in the IFC data model.

Metracker provides a user interface for organizing and visualizing the performance data generated by these other software tools.

The primary purpose of Metracker is therefore to illustrate how performance data are structured, and why life-cycle performance tracking is useful, so that other software tools can archive and access these data to better assure building performance. If Metracker properly serves this purpose, it may never advance beyond the prototype stage. Instead, the capabilities that it illustrates will be adopted and adapted by other software such as design analysis/simulation tools and energy management and control systems that feed and retrieve performance data to and from IFC data files in support of various performance assurance activities across the life cycle.

It is envisioned that in the future, owners will specify and archive their desired building performance in an IFC data file using a specifically tailored design performance specification application. The design team will then reference these desired performance specifications to guide design decisions. Software such as energy simulation tools that are used to evaluate alternative designs will then archive both the final design and its simulation results together in the evolving project IFC data file. Project participants performing subsequent activities such as commissioning can then retrieve this expected performance for comparison with in-situ measurements and archive new performance benchmarks. Any tool, used by any authorized participant, can thus access and update these data in support of current activity or the anticipated activity of downstream participants (e.g., building operators).

3.3.2. Elaborating Performance Objectives and Metrics

As discussed in Section 2.1, Performance Objectives and Metrics are organized hierarchically following a tree metaphor, with individual nodes aligned in branches leading away from a root node until they end in leaf nodes. Metracker creates such a hierarchy beginning with a root Performance Objective node as illustrated in Figure 4. Additional Performance Objectives can subsequently be created along any branch below this root node. In the current Metracker prototype, each node within a hierarchy like that shown in Figure 1 would be represented as a Performance Objective. One or more Performance Metrics, containing quantitative benchmark or assessment values, can then be created under each Performance Objective node. Conceptually, Performance Metrics could be delineated hierarchically in a fashion similar to that for Performance Objectives. However, to simplify the hierarchical structure within Metracker, the current implementation only allows Performance Metrics to be created as a list of children of a Performance Objective node. Performance Metrics cannot be nested within each other, and can only be leaf nodes under a Performance Objective parent in the current implementation.

- Root Performance Objective
  - Performance Objective 1
    - Performance Objective 1.1
      - Performance Metric 1.1.a
      - Performance Metric 1.1.b
    - Performance Objective 1.2
      - Performance Objective 1.2.1

Figure 4. Metracker Performance Model hierarchical tree organization.

Each Performance Objective has the following attributes: Name, Date of Specification, Objective Type, Specifier, and Description. The Name provides a user-defined identification. Objective Type is intended to be selected from a pre-defined set of key performance objectives agreed upon by industry consensus, however this attribute is user-defined at the current time. The Specifier is the person responsible for identifying an objective as important to the specific project at the recorded Date of Specification. The Description is a text statement describing the goal for a Performance Objective in more detail.

Each Performance Metric includes the following attributes: Name, Date of Specification, Specifier, Metric Type, Benchmark Type, Description, Source, Data Type, and Data Value(s). The metric Name is a text identifier that is intended in the future to be supplemented with a standardized code for a predefined set of performance metrics. The Specifier and Date of Specification document the building process participant concerned with each metric and its date of creation. The Metric Type identifies whether the metric is a Benchmark or an Assessment. Benchmarks specify the intended level of performance, while Assessments record actual (e.g., measured) levels of performance that are meant to be compared to Benchmarks. If the metric is of type Benchmark, then a Benchmark Type is selected from a prescribed list including the following: greater than, greater than or equal to, less than, less than or equal to, equal to, not equal to, target with tolerance, range, and distribution. Source documents the origin of a metric value. For Benchmark type metrics, the Source might be a code, standard, benchmark database, manufacturer data set, or other source of benchmark values. For an Assessment type metric, the Source could be a simulation, monitoring measurement, or other assessment method. The Data Type of a metric is selected from a list including the following: scalar, vector (bar chart), time series, table (2D XY plot), graph (3D XYZ plot), and distribution. The selected Data Type defines the style of data visualization, as described in more detail below. Lastly, the Data Value(s) are the quantitative metric values.

Figure 5 shows a screen shot from Metracker displaying an example hierarchy of Performance Objectives and Performance Metrics similar to that shown in Figure 1. The highlighted Performance Objective is named *Optimize Energy Performance*. Below this objective is another Performance Objective named *Whole Building Energy Use*. There are three archived Performance Metrics shown in this example that are children of the *Whole Building Energy Use* objective, one each for the original planning *Baseline*, the *Schematic* design estimate, and *As-Operated* for the year 1999. There are also Performance Objectives for each of the primary system energy uses that are children Objectives of *Whole Building Energy Use*. Each of these Objectives might ultimately have a list of children Metrics below each of them, and might be further delineated with children Objectives. In this manner, each Performance Objective can be parent to both a list of Metrics specific to that Objective, and a continuing branch of children Objectives.

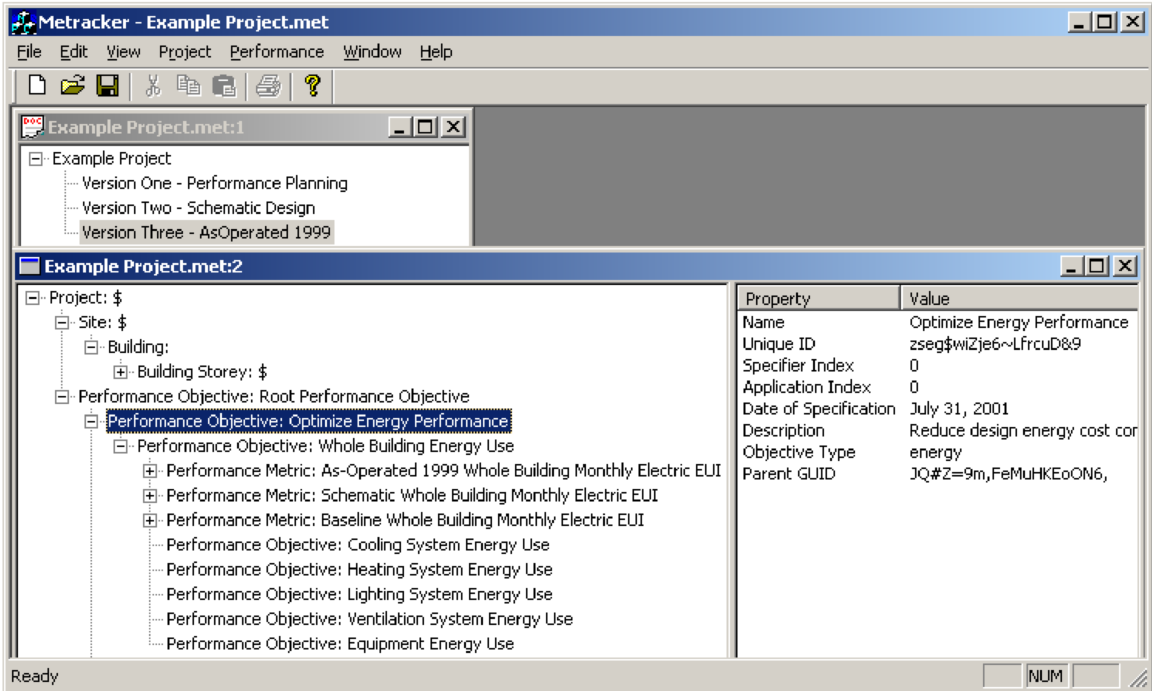

Figure 5. Metracker example hierarchy.

3.3.3. Archiving a History of Building Performance

As illustrated in Figure 3, multiple versions (or snapshots) of a project can be archived as the project moves through its life cycle. This is done to capture the state of both the product and performance models of the building at specific points in time. Metracker accomplishes this historical archive by organizing multiple IFC data files into a list referred to in Metracker as a Project. An example of such a list is shown in the upper left window in Figure 5, and contains three versions that have been archived as individual IFC data files. Each IFC file is stored separately so that other IFC-compliant software tools can access its data. In general, each new version will be a modification of the previous version, capturing changes that have been made primarily to the product model of the building (e.g., changes from design to as-built).

The set of objectives and metrics shown in the lower window in Figure 5 constitute the performance model for the highlighted version named "Version Three - AsOperated 1999" and illustrate the idea that each archived version can itself contain a series of Performance Metric snapshots. In this example, the highlighted Performance Objective "Optimize Energy Performance" is parent to a series of Performance Metric snapshots of "Whole-Building Monthly Electric Energy Use Intensity (EUI)." The three snapshots archive monthly data values for an initial Baseline, an update at the Schematic design phase, and As-Operated 1999 measurements. In this manner a history of both expected and actual performance is archived across changes to the building product model.

3.3.4. Performance Metric Data Visualization

A key aspect of tracking building performance is the ability to view and compare expected and actual performance over time. Metracker supports this capability by displaying graphs of the Performance Metric data archived within a given IFC data file. Currently Metracker graphs data of the following Data Types: Vector, 2D XY, Time Series, and frequency Distribution. Vector data are graphed as bar charts. 2D XY, Time Series, and frequency Distribution data are graphed as two-dimensional plots, where time series data produce plots with time as the X-axis.

There are two options available for visualizing Performance Metric data. The first option is to display a graph of the data set associated with an individual Performance Metric. Figure 6 shows an example of this option applied to the "As-Operated 1999 Whole Building Monthly Electric EUI" data set.

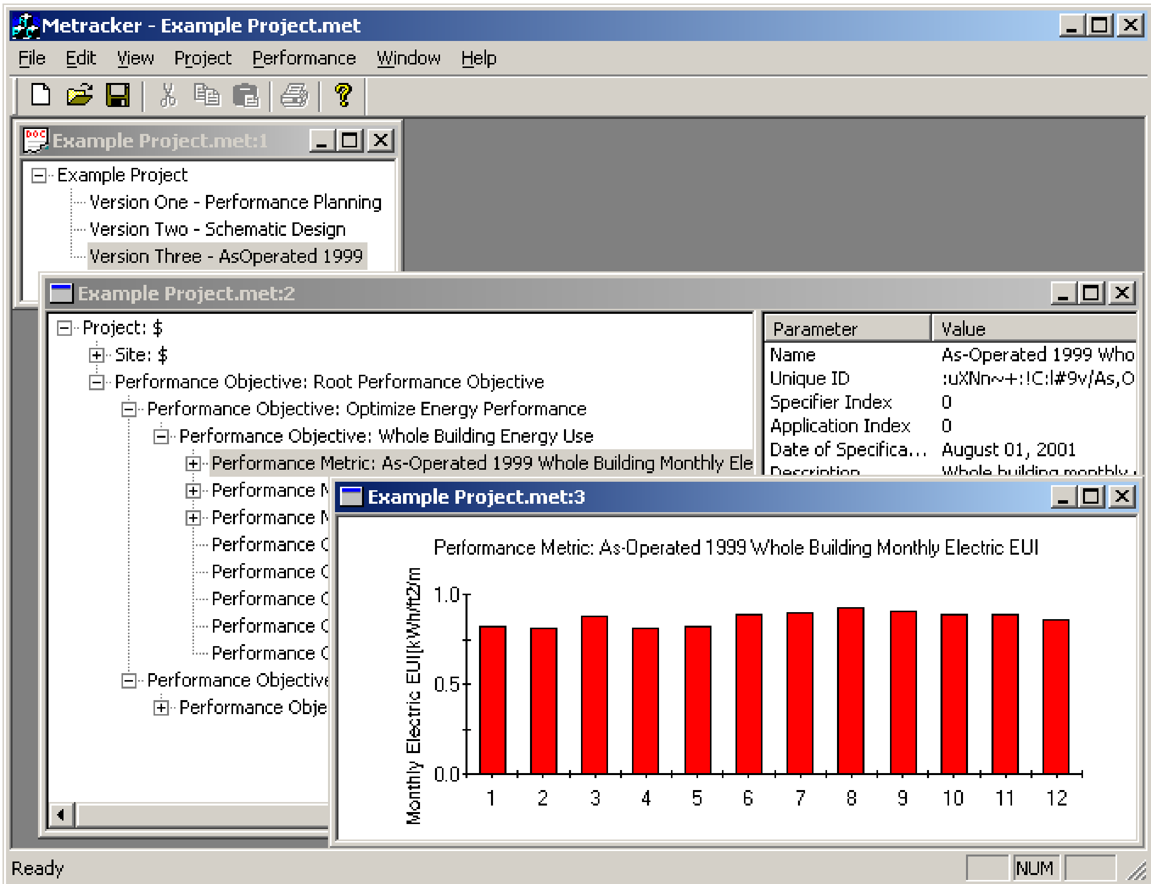

Figure 6. Graph of an individual Performance Metric data set.

The second data visualization option is to comparatively plot the data sets associated with all Performance Metrics that are children of a single Performance Objective on the same graph. Metracker can currently only graph multiple Performance Metric data sets if the Data Type is identical for all data sets. This could be enhanced in the future so that differing, but compatible data types could be graphed together for comparison (e.g., a scalar benchmark value along with a Time Series assessment). Figure 7 shows an example of this second visualization option applied to the multiple Performance Metric data sets archived as children of the "Whole Building Energy Use" Performance Objective.

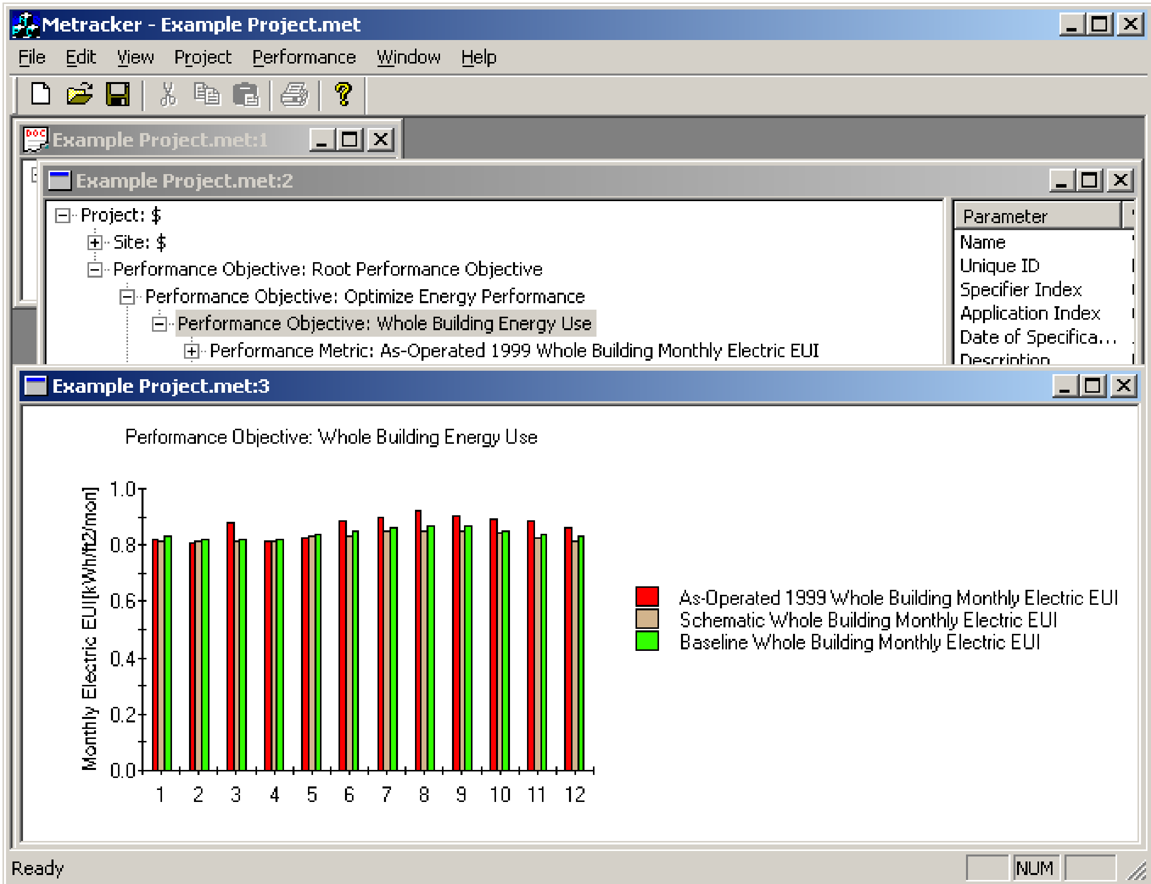

Figure 7. Comparative graph of multiple Performance Metric data sets.

4. A Review of Building Performance Frameworks

Others have previously developed a number of building and facility performance frameworks. This work ranges from ongoing efforts to prepare a comprehensive compendium of building performance models, such as the International Council for Building (CIB) Performance Based Building Program [6,7,8], to the development of a system for assessing the environmental impact of a building over its life cycle, such as the U.S. Green Building Council's LEED Green Building Rating System. A review of this work serves this current research both to leverage previous work and to better assure consistency with existing standards. Also, while the performance metric sets detailed in Section 5 focus on energy-related metrics, a review of standards such as the ASTM Standards on Whole Building Functionality and Serviceability [9] provides a broader context within which the energy performance of a facility must ultimately be assessed. Also, each of these efforts makes reference to energy-related objectives, without including fully elaborated quantitative metrics that can be used to assess the achievement of these objectives. For this reason, these efforts and the organizations that are undertaking them, may offer the means to move the results of this current research out into the commercial world.

This section describes several national and international efforts to develop comprehensive building performance frameworks. Section 5 will then present several sets of performance metrics that might be used to more fully elaborate the energy-related objectives within these frameworks.

4.1. CIB Performance Based Building [6,7,8,8a]

The International Council for Building (CIB, formerly Conseil International du Bâtiment) has identified Performance Based Building as one of its "priority themes." The CIB Board has recommended that a program be established with a focus on preparing a compendium of validated models of building performance. Within this CIB context building performance models refer to "computational procedures and/or computer programs that can be used in developing quantitative performance criteria for building codes and standards, designing a building to a target performance, or evaluating a given design (or product) for each level in the building performance hierarchy (from the whole building to individual elements or materials)" [8].

The end product of this program is intended to be the first edition of a publication entitled "CIB Compendium of Building Performance Models." "This compendium will provide a framework that can be populated with new or revised models as they become available. The compendium will be structured to parallel an envisaged performance-based building code or regulatory document, organized according to building attributes or user needs," with a hierarchy of building parts, from whole building to individual elements or materials, under each attribute [8].

It is significant that the international building community is thinking along these lines. This is a major undertaking, and current participants recognize that collating such a compendium will require substantial contributions from outside the program's core group. While related work continues within a number of CIB Task Groups and Working Commissions, it does not appear that this proposed compendium has been published at this time.

The initial framework that has been developed for organizing this compendium of models is shown below in Figure 8 [8]. The original source of this framework was the VTT ProP performance classification developed by VTT [8a]. In several ways this framework is of greater relevance to the task of standardizing performance metrics than the final compendium of computational procedures for calculating values for the metrics. This framework is one example of an inclusive hierarchy of building performance characteristics that are critical to overall building functionality, including safety, comfort, health and hygiene, durability, and sustainability.

Note that the category of energy conservation (5.1) falls under the topic of sustainability (5) in this hierarchy, and is delineated by the following subcategories: whole building, frame/wall system, roof/floor system, foundation, and components/materials (5.1.1-5.1.5). The hierarchy does not contain a further breakdown of whole building energy conservation, nor any specific mention of energy-consuming systems such as HVAC, lighting, and equipment. However, the hierarchy does provide a higher-level framework that places building energy performance within a broader context of overall building performance.

1 Safety

- 1.1 Structural safety (W023, TG32, SEAOC, SEI-ASCE, ACI, AISC, RILEM, ISO, ASTM, EERI, etc)
  - 1.1.1 Whole structure
  - 1.1.2 Frame/wall system
  - 1.1.3 Floor/diaphragm system
  - 1.1.4 Member
  - 1.1.5 Connection
  - 1.1.6 Foundation

- 1.2 Fire safety (W014, TG37, IFSEI, SFPE, NIST, IRC, CSIRO, BRE, Andy Buchanan, Rachel Becker, Jean-Marc Franssen, etc)
  - 1.2.1 Whole building
  - 1.2.2 Frame/wall system
  - 1.2.3 Floor system/roof
  - 1.2.4 Other building parts (e.g., door)
  - 1.2.5 Member/materials
  - 1.2.6 Services
- 1.3 Safety in use *(ISO, ASTM, etc)*
  - 1.3.1 Whole building
  - 1.3.2 Frame/wall system
  - 1.3.3 Roof/floor system
  - 1.3.4 Other building parts/members/materials
  - 1.3.5 Services

2 Comfort

- 2.1 Acoustical comfort (W051, Intl Institute of Noise Control Engineering, ASA, Fraunhoffer Institut fur Bauphysik, etc)
  - 2.1.1 Whole building
  - 2.1.2 Frame/wall system
  - 2.1.3 Floor system/roof
  - 2.1.4 Components
  - 2.1.5 Connections
  - 2.1.6 Materials
  - 2.1.7 Services
- 2.2 Visual comfort (Intl Commission on Illumination, LBL, Steve Selkowitz, etc)
  - 2.2.1 Whole building
  - 2.2.2 Windows
  - 2.2.3 Shading devices (blinds)
  - 2.2.4 Light caps
  - 2.2.5 Light shelves
  - 2.2.6 Wall
- 2.3 Hygrothermal comfort (W040, W077, IEA, IBPSA, AIVC, ASHRAE, NIST, IRC, NBRI, CSIRO, etc)
  - 2.3.1 Whole building
  - 2.3.2 Frame/wall system
  - 2.3.3 Roof/floor system
  - 2.3.4 Member/materials
  - 2.3.5 Services
- 2.4 Structural serviceability (W085, W023, SEI-ASCE, ISO, IRC, CSIRO, etc)
  - 2.4.1 Whole building
  - 2.4.2 Frame/wall system
  - 2.4.3 Floor system/roof
  - 2.4.4 Member/materials
  - 2.4.5 Services

3 Health and Hygiene

- 3.1 Air quality (TG 28, ISIAQ, ASHRAE, NIST, IRC, CSIRO, NBRI, Fanger, etc)
  - 3.1.1 Whole building
  - 3.1.2 Frame/wall system
  - 3.1.3 Floor system/roof
  - 3.1.4 Components
  - 3.1.5 Materials
  - 3.1.6 Services
- 3.2 Water Supply and other services *(W062)*
- 3.3 Waste Disposal *(W062)*

4 Durability

- 4.1 Structure (W080, W083, W094, TG22, ISO, TNO, NIST, IRC, BRI, CSTB, CSIRO, C. Sjostrom, M. Lacasse, etc)
  - 4.1.1 Whole building
  - 4.1.2 Frame/wall system
  - 4.1.3 Roof/floor system
  - 4.1.4 Member/materials
  - 4.1.5 Foundation

4.2 External enclosure (W080, W083, W094, W040, TNO, NIST, IRC, BRI, CSTB, CSIRO, NBRI, C. Sjostrom, M. Lacasse, etc)
4.2.1 Below ground
4.2.2 Above ground
4.3 Internal enclosure *(W080, W083, W094, W040, TNO, NIST, IRC, BRI, CSTB, CSIRO, etc)*
4.3.1 Below ground
4.3.2 Above ground
4.4 Built-in furnishings and equipment
4.5 Services
5 Sustainability
5.1 Energy conservation (W067, W100, IEA, NIST, IRC, BRI, CSTB, CSIRO, LBL, etc)
5.1.1 Whole building
5.1.2 Frame/wall system
5.1.3 Roof/floor system
5.1.4 Foundations
5.1.5 Components/Materials
5.2 Green-house Gas Depletion
5.2.1 Whole building
5.2.2 Structure
5.2.3 Other parts/materials
5.2.4 Services
5.3 Economics (W055, W092, NIST, CSIRO, etc)
5.4 Deconstruction/demolition and disposal (TG39, etc)

Figure 8. Overall framework for CIB Compendium of Building Performance Models [8, 8a].

(Listed by permission of CIB Secretary General, W. Bakens)

4.2. ASTM/Whole Building Functionality and Serviceability [9, 10]

The ASTM Standards on Whole Building Functionality and Serviceability, Second Edition [9] is a compendium of ASTM standards used for defining the functional requirements for a building or facility based on its intended occupancy and use, and rating the level at which a particular facility meets these requirements. These standards identify a full range of functional requirements that might apply for a given building use, including various aspects of supporting occupant effectiveness and of maintaining and operating the building. The standards do not specify an appropriate level for each of the functional requirements. Rather, they provide a framework and process for elaborating the desired levels for a given building use, and assessing the capability of alternative facilities to meet these levels [10]. As such, they are similar in concept to the overall intent of this research, which is to provide a framework for elaborating the desired performance of a building and then assessing the achievement of this performance over time.

The technical publication containing these standards is organized into five sections. The first two sections contain 17 classifications of requirements that should be considered when rating the functionality and serviceability of a facility, and a procedure for identifying and setting levels for the requirements deemed relevant to a particular use. These classifications are organized hierarchically similarly to the CIB framework shown in Figure 8. The top level of this hierarchy contains two categories, *Occupant's Group and Individual Effectiveness* and *The Property and its Management*. The 17 classifications are grouped under each of these categories, with individual requirements appearing at the fourth and fifth levels of the hierarchy under each classification.

The end-user of this ASTM standard first selects the relevant requirements for a specific building project and then assigns the desired performance rating (referred to as a Benchmark in Section

3.3.2 above) for that requirement using a relative rating scale of 1 to 9, with higher values indicating increasing stringency in meeting the requirement. There is additional text associated with each requirement that more fully defines the differences between a performance rating of 1 and that of 9. An assessment of alternative building designs, or of building performance over time, can then compared to the established baseline.

The energy-related requirements that are identified within the ASTM hierarchy are shown in Figure 9 and are classified under the category of *The Property and its Management*. This is a fairly limited set of individual requirements, but at least serves to include energy considerations along with all other facility requirements.

B. The Property and its Management
- B.2. Manageability
  - B.2.7 Energy Consumption
    - *B.2.7.1. Requirement for Heating and Cooling Costs*
      - B.2.7.1.1. Building Envelope and Systems
      - B.2.7.1.2. Effects
  - B.2.8 Energy management and controls
    - *B.2.8.1. Level of Energy Management and Controls*
      - B.2.8.1.1. Energy System Components
- B.3 Management of Operations and Maintenance
  - B.3.4 Information on Unit Costs and Consumption
    - *B.3.4.1. O&M Staff Understanding of Practices and Costs*
      - B.3.4.1.1. Database on O&M Operations
      - B.3.4.1.2. Comparison with Recognized External Standards and Practices
      - B.3.4.1.3. Knowledge of Building Operational Parameters and Costs
      - B.3.4.1.4. Use of Information for Effective O&M Operations

Figure 9. Excerpted energy related requirements within the ASTM classification hierarchy [9, 10].

(Listed by permission of ICF President, G. Davis)

Also, the text that describes how to establish a performance rating for these energy-related requirements comes very close to the concepts of performance metrics tracking. For example, the description of a performance rating of 9 for the requirement of *O&M Staff Understanding of Practices and Costs* includes the following details [9]. "Data on fuel consumption and costs must be accurate and complete, with data for the current and previous three years organized for convenient analysis. These data must include sub-metering for lighting, convenience power, heating and cooling, reprographics, food service, and other fuel consumptions, with unit electrical and fuel costs. Data must be assembled in appropriate units for external comparison (e.g., therms/ft^2, \$/m^2, etc.). Relevant comparative data must be regularly obtained regarding best-in-class and typical from BOMA Experience Exchange Report or IFMA Benchmarks. Baseline costs should be estimated from compliance with standards and operating targets, with actual and baseline reported and analyzed monthly. Variance in current operations should be analyzed, and comparisons should be made to external standards and practices, leading to appropriate action plans."

The combination of the hierarchical classification of requirements for whole-building functionality, and the textual details of establishing ratings related to these requirements, makes this ASTM standard especially relevant to the research described in this report. This ASTM standard could well serve as a future host for the standardized energy performance metrics defined in Section 5 below.

The fourth section of this technical publication is entitled *Guide for Energy Monitoring and Data Gathering* and describes how to develop protocols for collecting facility energy performance data that will ensure that measurements are consistent and meaningful [9]. This section goes into some detail on energy use indexes (EUI, measured in $kBtu/ft^2$) and building performance indexes (BPI, measured in $kBtu/ft^2$-DegreeDay), but falls short of defining a complete set of energy performance metrics.

There are two other sections of this publication. *Floor Area Measurement* defines standard space charge-back protocols. *Terminology of Facility Management* attempts to standardize terms and definitions related to the performance of buildings and facilities.

4.3. ICC (International Code Council) Performance Code for Buildings and Facilities [11, 12]

The International Code Council (ICC) is an organization created to develop a single set of comprehensive and coordinated national model construction codes from the currently separate sets of model codes, and their regionalized derivatives. This effort is an attempt to improve the consistency of code enforcement and ultimately the overall quality of the constructed environment [11].

One product of this effort is the development of the ICC Performance Code for Buildings and Facilities [12]. This code is billed as the "first broad-based, stand-alone performance code in the nation [11]." The code "defines the objectives for achieving the intended outcomes regarding occupant safety, property protection and community welfare. It provides a framework to achieve the defined objectives in terms of tolerable levels of damage and magnitudes of design events, such as fire and natural hazards [12]." A prescriptive code prescribes the details of a single design solution. A performance code allows a user to explore a variety of solutions that meet or exceed the intended performance. The ICC Performance Code for Buildings and Facilities is currently available for adoption and use by both national and international code jurisdictions.

Similarly to the CIB and ASTM efforts discussed above, the ICC performance code provides a hierarchical framework within which energy-related performance issues fit. The top-level categories identified by the ICC performance code are shown in Figure 10 and correspond to chapters within the code documentation. The majority of these chapters focus on safety issues. Several chapters are further delineated at lower levels, referred to as sections, which are not shown in the figure. Chapter 15 within this framework focuses on Energy Efficiency and has only one section as discussed below.

4. Reliability and Durability
5. Stability
6. Fire Safety
7. Pedestrian Circulation
8. Safety of Users
9. Moisture
10. Interior Environment
11. Mechanical
12. Plumbing
13. Fuel Gas
14. Electricity
15. Energy Efficiency
16. Fire Prevention
17. Fire Impact Management
18. Management of People
19. Means of Egress

20. Emergency Notification, Access and Facilities
21. Emergency Responder Safety
22. Hazardous Materials

Figure 10. Framework from the ICC Performance Code for Buildings and Facilities [12].

Although the intent of the ICC performance code is to define the desired performance of a building or facility with respect to each of these categories, this definition is stated within the code only in descriptive text. There are no quantitative performance metrics defined within this code framework. The code does include an Objective, Functional Statement(s), and Performance Requirement(s) under each section within a chapter. However, the introduction to the code specifically states that performance criteria (defined as measurable examples) are not part of the code.

A more detailed look at the chapter on Energy Efficiency will illustrate the level of detail defined in the ICC performance code. The text of this chapter is shown in Figure 11. The stated objective is simply "to facilitate efficient use of energy." The functional statement does not add much to this objective. There are then two performance requirements identified to achieve the objective. The first of these requirements is numbered 1501.3.1 and requires that the building envelope be designed to meet regionalized indexes that specify the amount of energy passing through the envelope given a specific temperature differential between the inside and out. Adherence to this type of requirement would mean that a benchmark value for the index would have to be specified, and the actual performance of the envelope would have to meet or exceed this value. Performance Requirement 1501.3.2 goes a bit beyond this simple envelope index to identify other issues that should be taken into consideration to achieve the objective of energy efficiency.

This descriptive type of performance requirement falls short of the type of performance metric tracking envisioned by this research. However, the ICC performance code both provides a larger context framework for including energy efficiency in design and operation considerations, and identifies a variety of objectives that correspond closely to the qualitative "performance objective" concept within this research.

Chapter 15 ENERGY EFFICIENCY

SECTION 1501 ENERGY EFFICIENCY

1501.1 Objective. To facilitate efficient use of energy.

1501.2 Functional statement. Buildings shall have provisions ensuring efficient use of nonrenewable energy.

1501.3 Performance requirements.

1501.3.1 *To provide for the efficient use of depletable energy sources, the building envelope must be designed and constructed within stated parameters. These parameters are called the* energy performance indexes. *These indexes are the amount of energy from a depletable energy source passing through a specified building envelope area during a specified difference in internal and external temperature. These indexes are based on the region of the country as well as the use of the building. Equivalent energy performance utilizing alternative energy conservation techniques is permitted. In some cases, for certain types of buildings, the local jurisdiction may choose not to specify energy performance indexes.*

1501.3.2 *For buildings requiring a controlled temperature, the building design and construction must take into account various factors. Normally, only insulation, types of windows and related building elements are considered when addressing energy conservation. However, to provide for the efficient use of energy, there are several other items that need to be taken into consideration, such as thermal resistance, solar radiation, air tightness and heat gain or loss from building services.*

Figure 11. ICC performance code text from Chapter 15 on Energy Efficiency [12].

4.4. USGBC/LEED [13]

Probably the most widely known building performance framework within the U.S. environmental community is the LEED Green Building Rating System. LEED stands for Leadership in Energy and Environmental Design and was developed by the U.S. Green Building Council (USGBC) [13]. LEED is a rating system that evaluates the environmental performance of a facility from a whole-building perspective over a building's life cycle. The framework of LEED is organized under five categories as shown in Figure 12. A set of Prerequisite requirements and optional Credits are identified within each of these categories. Each Prerequisite or Credit is elaborated with descriptive statements related to its Intent and Requirement(s), and advice on Technologies/Strategies that can be employed to earn the prerequisite or credit. Rating points are given for the achievement of each Credit, and an overall building rating is based on the total number of these points.

Sustainable Sites
- Prerequisite: Erosion and Sedimentation Control
- Credit 1: Site Selection
- Credit 2: Urban Redevelopment
- Credit 3: Brownfield Redevelopment
- Credit 4: Alternative Transportation
- Credit 5: Reduced Site Disturbance
- Credit 6: Storm water Management
- Credit 7: Landscape and Exterior Design to Reduce Heat Islands
- Credit 8: Light Pollution Reduction

Water Efficiency
- Credit 1: Water Efficient Landscaping
- Credit 2: Innovative Wastewater Technologies
- Credit 3: Water Use Reduction

Energy and Atmosphere
- Prerequisite 1: Fundamental Building Systems Commissioning
- Prerequisite 2: Minimum Energy Performance
- Prerequisite 3: CFC Reduction in HVAC&R Equipment
- Credit 1: Optimize Energy Performance
- Credit 2: Renewable Energy
- Credit 3: Additional Commissioning
- Credit 4: Elimination of HCFC’s and Halons
- Credit 5: Measurement and Verification
- Credit 6: Green Power

Materials and Resources
- Prerequisite: Storage & Collection of Recyclables
- Credit 1: Building Reuse
- Credit 2: Construction Waste Management
- Credit 3: Resource Reuse
- Credit 4: Recycled Content
- Credit 5: Local/Regional Materials
- Credit 6: Rapidly Renewable Materials
- Credit 7: Certified Wood

Indoor Environmental Quality
- Prerequisite 1: Minimum IAQ Performance
- Prerequisite 2: Environmental Tobacco Smoke (ETS) Control
- Credit 1: Carbon Dioxide (CO2) Monitoring
- Credit 2: Increase Ventilation Effectiveness
- Credit 3: Construction IAQ Management Plan
- Credit 4: Low-Emitting Materials
- Credit 5: Indoor Chemical and Pollutant Source Control
- Credit 6: Controllability of Systems
- Credit 7: Thermal Comfort
- Credit 8: Daylight and Views

Figure 12. The LEED framework [14].

Similarly to the ICC performance code, the elaboration of prerequisites and credits within LEED is given in descriptive text. The key LEED items related to energy performance serve as examples of this elaboration. These items are located under the category of Energy and Atmosphere.

Energy and Atmosphere Prerequisite 2 is entitled “Minimum Energy Performance” with the stated Intent of establishing “the minimum level of energy efficiency for the base building and systems [14].” The associated Requirement is to design the building to meet the energy performance required by ASHRAE/IESNA 90.1-1999 [18] or the local energy code whichever is more stringent. Compliance with this requirement is to be shown by using the system/component method, which is a prescriptive approach.

Energy and Atmosphere Energy Credit 1 is entitled “Optimize Energy Performance” with the Intent of achieving increasing levels of energy performance above the prerequisite level. Additional points are given for each incremental improvement up to a possible ten points. Achievement of this credit is demonstrated using building simulation to calculate and compare baseline (benchmark) and proposed design (assessment) values for annual energy cost expressed in dollars. This method is referred to as the Energy Cost Budget method (ECB).

The performance metric concepts developed in this research would apply especially well within the context of LEED. In particular, the documentation and archival of the myriad details related to comparative building energy simulation that is supported by the Metracker concepts could serve the users of LEED well. This topic is discussed in more detail in Sections 4.6 and 5.6 below.

4.5. US DOE High-Performance Buildings Metrics Project [15, 16, 17]

A recent development within the area of building performance metrics is the ongoing effort by the US Department of Energy (DOE) to define a framework for organizing parameters, metrics, and data that quantitatively characterize the performance of buildings [15]. This effort is ultimately intended to lead to a database of building performance data and information useful in improving the overall performance of buildings.

Two products that have come out of a Spring 2002 Workshop sponsored by this project are working draft documents describing a building performance metrics framework [16], and identifying specific performance metrics related to the topic area of Resource Consumption and Environmental Loading of Energy Use [17]. The information contained in these draft documents has evolved from discussions and breakout group sessions at this and prior performance metric workshops [15].

The proposed framework that has resulted from this project is described here. The Resource Consumption and Environmental Loading of Energy Use performance metrics are described in Section 5.

4.5.1. High Performance Buildings Metrics Project Framework [16]

The proposed framework for the High-Performance Buildings Metrics Project identifies seven categories of parameters that define high-performance buildings. These categories are shown in Figure 13 and represent the top-level of a hierarchically organized set of performance metrics. Examples of second-level classifications for individual metrics are also shown in this figure. This framework is a preliminary proposal at this stage of the project. It is a starting point from which to "define the issues that should be included in measuring building performance for the project and … be used in designing [a building performance] database, forming work groups, proposing metrics, and conducting research [16]."

1. **Reduce and/or eliminate use of finite resources for energy production and other activities.**
    1.1. Land use/ site selection
    1.2. Water Consumption
    1.3. Materials
    1.4. Energy
2. **Reduce environmental loadings over the full lifecycle of the building related to energy consumption and other activities.**
    2.1. Global warming potential
    2.2. Ozone depletion
    2.3. Ground level ozone
    2.4. Nutrification/ eutrophication
    2.5. Acidification
    2.6. Human health/toxic releases to land
    2.7. Human health/toxic releases to air
    2.8. Human health/ toxic releases to water
3. **Protect and restore the health of whole ecosystems.**
    3.1. Habitat
    3.2. Biodiversity
4. **Promote individual occupant health and well-being.**
    4.1. Health
    4.2. Productivity
    4.3. Comfort
5. **Promote organizational occupant effectiveness and success.**
    5.1. Flexibility/ adaptability
    5.2. Durability/ reliability
    5.3. Safety/ security
    5.4. Facility management/ O&M
    5.5. Customer satisfaction
6. **Support livable "high-performance" communities.**
7. **Make economic sense.**

Figure 13. Proposed framework for the US DOE High-Performance Metrics Project [16].

This framework falls somewhere between the LEED and ASTM frameworks discussed above. It has a strong emphasis on energy and environmental issues, but also includes issues related to occupant effectiveness. It is anticipated that the US DOE efforts will primarily focus on further elaborating metrics within the energy portions of this overall framework, and seek alliances with other organizations that are interested in elaborating the remaining portions. It is not the intent of this effort to duplicate ongoing efforts of other organizations, but rather to meld the products of other efforts into some version of the framework shown above. The primary objective of the project is "to advance the *science* of performance metrics, thereby improving our ability to measure what we have accomplished and how we have achieved it [16]."

4.6. Summary of Building Performance Frameworks

Five frameworks for organizing building performance objectives have been described above. Each of these frameworks targets its own audience and therefore differs in its performance classification scheme and in the building performance issues that it addresses. However, performance objectives related to building energy efficiency are common to all of these frameworks. As illustrated by the treatment of energy-efficiency within the ICC Performance Code for Buildings and Facilities [12] and to an extent even by the USGBC LEED Rating

System [14], these frameworks tend to lack quantifiable metrics that can be used to specify and track the energy performance of buildings in the manner developed within this research. Yet a stated objective for developing each of the above frameworks is to improve and assure the overall performance of a building.

To repeat a quote from the CIB Performance Based Building Program discussed above, a primary objective of this program is to identify and classify "computational procedures and/or computer programs that can be used in developing ***quantitative performance criteria for*** building codes and standards, ***designing a building to a target performance, or evaluating a given design (or product) for each level in the building performance hierarchy (from the whole building to individual elements or materials***)" [8, italics added here]. The CIB effort has not yet reached this level of detail.

The ASTM Standards on Whole Building Functionality and Serviceability describe the level of detail regarding fuel consumption and cost that is necessary to achieve the highest performance rating for operations and maintenance (O&M) practices. The ASTM description includes statements such as "these data must include sub-metering … with unit electrical and fuel costs," "data must be … in appropriate units for external comparison," and "current operations should be analyzed, and comparisons should be made to external standards and practices, leading to appropriate action plans"[9]. Aside from including generic examples of appropriate metrics within this description, the ASTM standards do not provide an organized set of standardized performance metrics. Such a standardized set should prove quite useful to a building project employing these ASTM standards.

A flow chart within the ICC Performance Code for Buildings and Facilities document illustrates how the code is intended to work. This chart includes measurable performance criteria, with verification and documentation steps leading to a final design solution [12]. However, these elements within the overall process are explicitly shown as not being part of the ICC code, and must therefore be obtained from some other source.

The LEED Green Building Rating System includes the ability to earn from two to ten additional credits for incremental improvements in energy efficiency out of a possible total of 69 points. These incremental improvements are defined within LEED documentation only as increasing percentage reductions in design energy cost in comparison to an energy cost budget resulting from ASHRAE/IESNA Standard 90.1-1999 [18]. The developers of LEED have recognized that this definition is not explicit enough for consistent and accurate application. The developers of the ASHRAE standard are in the process of drafting an addendum to Standard 90.1 that will address this problem [19]. The addendum defines the procedures to be followed in modeling and simulating both a baseline building design and a proposed building design for purposes of calculating and comparing their energy cost. These procedures are intended to support performance rating methods such as LEED that require only a single performance metric such as *percent reduction in whole-building annual energy cost compared to a standard*. Yet, the building project resources spent in following these procedures could be leveraged to generate a host of additional whole-building and system performance metric values useful in assuring the overall performance of a building over time. Standardized sets of performance metrics would be extremely helpful in supporting such a follow-on effort since these sets clearly identify the key metrics that should be tracked across the building life cycle.

Thus, each of these five frameworks is a candidate for incorporating standardized energy-related performance metrics within a larger context of building performance. However, only the U.S. DOE High Performance-Buildings Metrics Project has taken the step of identifying specific metrics that could be used to support the type of performance tracking envisioned by this current research. The next section of this report will present candidate sets of performance metrics, including the current set from the DOE project, that could be used to more fully elaborate the energy-related objectives within these performance frameworks.

5. Standardized Performance Metric Sets

To reiterate from Section 2.1, performance metrics as defined within this research, are intended to explicitly represent the performance objectives for a building project, using quantitative criteria, in a dynamic, structured format. One or more metrics may be identified for each performance objective that building process participants wish to specify and track. A guiding principle in selecting a performance metric is to identify a critical variable that measures, reflects, or significantly influences a particular performance objective. To be useful across the building project life cycle, each metric must also be capable of being either predicted or measured at various stages of the project so that the achievement of the associated objective can be evaluated.

This section presents several sets of energy-related performance metrics that have been defined by various efforts in this area. Each of these sets is a candidate for standardization within an individual building project to support performance tracking over time, across projects that wish to make comparisons between multiple buildings, and/or in the development and use of a building performance database to support benchmarking and related procedures.

Section 5.5 “Instantiating Standardized Performance Metric Sets in Metracker” discusses how these metric sets can be added to an IFC project file for tracking performance for a given building project.

5.1. US DOE High-Performance Buildings Metrics Project - Performance Metrics related to Resource Consumption and Environmental Loading of Energy Use [17]

The workshops that have been sponsored by the U.S. DOE High-Performance Buildings Metrics Project to date have been organized around a combination of whole-group discussion and breakout sessions of smaller groups focused on categories similar to those shown in the framework in Figure 13. During the Spring 2002 Workshop one of these breakout groups focused on the issue of measuring energy use in buildings, and the overall impacts due to this energy use. Building on similar breakout group discussions from previous workshops, this group elaborated specific performance metrics within a topic area entitled “Resource Consumption and Environmental Loading of Energy Use” [17]. The performance metrics identified by this breakout group cut across the first two categories in the above framework.

The Resource Consumption and Environmental Loading of Energy Use metrics are shown in Figure 14. These metrics are intended to support assessment of resource consumption and environmental loading at both the site of the energy use and at the source where this energy was generated. It is anticipated that each metric will therefore have separate site and source values, and that both quantity and cost values will be determined for each of these where appropriate.

Also, separate values should be calculated for each metric by energy type. This provides flexibility in the ways in which these individual metric values can be aggregated.

For convenience, the breakout group agreed to use specific British units of measurement to represent more generic units. For example, kBtu is used in Figure 14 as a generic unit of energy consumption that would ultimately be specialized for a particular energy type. Similarly, "ft^2" is used as a generic unit of area, and "yr" as a generic unit of time. Thus, a unit of measurement of "kBtu/ ft^2-yr" associated with a metric like "Normalized Whole Building Energy Use" is intended to imply that this metric can be measured or calculated using any appropriate units for energy, area, and time. However, the specific units that are ultimately used must be explicitly documented at the time of instantiation.

Additional units of measurement, as well as new performance metrics, will be identified in the future as further consideration of the audience for these metrics evolves. For example, building owners might be most interested in metrics with units of measurement that relate energy use to the number of building occupants or to the productive output of a facility. Alternatively, building operators might generally find energy use per unit area over small time increments more useful in supporting their activities.

There are three levels of metrics listed below that represent increasing detail. The breakout group spent the most time and discussion on the Level I Metrics so as to identify key metrics that would support the assessment of the primary impacts of building energy use. Level II Metrics are simply disaggregated energy end uses and peak demands. Level III Metrics were initially identified during previous workshop discussions and are listed here as rough examples. It should be noted that the list of performance metrics in Figure 14 is only a starting point in need of further refinement. However, it gives a good example of the intended final product of this effort related to performance metrics.

- **Normalized Whole Building Energy Use [by energy type] (kBtu/ft^2-yr, \$/ft^2-yr)**
  - Normalized Heating Energy Use [by energy type] (kBtu/ft^2-yr, \$/ft^2-yr)
  - Normalized Cooling Energy Use [by energy type] (kBtu/ft^2-yr, \$/ft^2-yr)
    - Cooling Equipment Efficiency (kW/ton)
    - Cooling Equipment Sizing (tons/ft^2)
  - Normalized Lighting Energy Use [by energy type] (kBtu/ft^2-yr, \$/ft^2-yr)
    - Lighting Equipment Efficiency (fc/W)
    - Lighting Equipment Sizing (W/ft^2)
  - Normalized Ventilation Energy Use [by energy type] (kBtu/ft^2-yr, \$/ft^2-yr)
    - Ventilation Equipment Efficiency (W/cfm)
    - Ventilation Equipment Sizing (cfm/ft^2)
  - Normalized Process Loads Energy Use [by energy type] (kBtu/ft^2-yr, \$/ft^2-yr)
    - Normalized Disaggregated Process Loads Energy Use [by load type] (kBtu/ft^2-yr, \$/ft^2-yr)
  - Normalized Plug Loads Energy Use [by energy type] (kBtu/ft^2-yr, \$/ft^2-yr)
- **Normalized Atmospheric Emissions [by emission type] (lbs of emissions/ft^2-yr, \$/ft^2-yr)**
- **Normalized Water Consumption [by end use] (ft^3/ft^2-yr, \$/ft2-yr)**
- **Normalized Water Pollution [by end pollution element/impact] (ft^3/ft^2-yr, \$/ft2-yr)**
- **Peak Demand [by fuel type, Annual, Daily, and Design Peak] (kBtu/hr-ft^2, \$/ft2-yr)**
  - Heating Peak Demand [by fuel type, Annual, Daily, and Design Peak] (kBtu/hr-ft^2, \$/ft2-yr)
  - Cooling Peak Demand [by fuel type, Annual, Daily, and Design Peak] (kBtu/hr-ft^2, \$/ft2-yr)

Figure 14. Resource Consumption and Environmental Loading of Energy Use performance metrics [17].

Two additional lists of data elements were also identified during this breakout group session. These lists were categorized as "metric calculation variables" and "database filtering variables." Metric calculation variables are those that are required to calculate identified metrics. Database filtering variables are those that can be used to filter subsets of comparable buildings in a performance database. The list of metric calculation variables is shown in Figure 15. The list of identified database filtering variables is shown in Figure 16. It should be noted that all of these data elements would be included in an IFC data file that archived performance metric data along with a complete building model.

- **Building Description**
  - Building Size
    - Gross Floor Area
    - Conditioned Floor Area
  - Location
    - Weather
  - Energy Rate Structure by Fuel Type
  - Unit of Productivity
  - Occupancy
    - Occupants
    - Occupied Hours/Time
- **Energy**
  - Energy Use by Fuel Type at Site and Source
    - Sub-metered Energy Use by End Use by Fuel Type at Site and Source
  - Peak Demand by Fuel Type at Site and Source
    - Sub-metered Peak Demand by End Use Fuel Type at Site and Source
- **Atmospheric Emissions**
  - Pounds of Emissions by Pollutant Type at Site and Source
- **Water**
  - Consumption at Site and Source
  - Pollutant quantities at Site and Source (need help)

Figure 15. Metric calculation variables.

- **Building Description**
  - Building Type and Use
  - Building Size by Use
    - Gross Floor Area
    - Conditioned Floor Area
    - Stories
  - Location
    - Weather
    - Utility Service Area
    - Air Shed
    - Water Shed
  - HVAC System Type
  - Special Design Features
    - Daylit
    - Naturally ventilated
    - etc.
  - Rented vs. Owner Occupied

Figure 16. Database filtering variables.

5.2. ANSI/ASHRAE Standard 105-1984 (RA 99) [5]

The ANSI/ASHRAE Standard 105-1984 (RA 99) is entitled "Standard Methods of Measuring and Expressing Building Energy Performance." The stated purpose of this standard is to "provide a consistent method of measuring and expressing the energy performance of buildings and to provide minimum requirements for and aid in the formation of a building energy performance database [5]." The standard is intended to "facilitate comparison, design and operation improvements, and development of building energy performance standards [5]."

Standard 105 includes considerable detailed information including procedures and minimum requirements for measuring energy performance in existing buildings, estimating performance in new buildings, and expressing (i.e., documenting) this energy performance. This information includes methods for measuring energy consumption, frequency and duration of these measurements, units of measurement for various forms of energy, and a minimum set of associated building characteristics. The standard also includes the minimum requirements for a database containing these measurements that could then be used to generate a building energy performance standard. Several appendices that are not officially part of the standard identify methods of classifying building occupancy/use and its associated industry that would lead to the type of database filtering variables described above.

Another appendix that is not officially part of the standard contains a three-level hierarchy provided for the purpose of reporting the functional uses and quantities of each form of energy used in the building. This hierarchy is the equivalent of a performance metric set. While the hierarchy does not include units of measurement within it, these details are fully covered in earlier sections of the standard. The hierarchy is shown in Figure 17.

It should be noted that the term *energy performance* is defined within Standard 105 as the energy *consumption* or *use* for a building. Thus, the recommended units of measurement include kilowatt-hour and Btu rather than normalized values that include factors of time and area. Given sufficient coincident data regarding these other factors, values for energy performance similar to those shown in the top two levels of Figure 14 can be readily calculated for each of the elements in the hierarchy below. However, equipment efficiency metrics such as those shown in the third level of Figure 14 would require additional data points beyond the minimum requirements identified in Standard 105.

1. Heating
- 1.1 Initial or prime heating equipment
- 1.2 Supplementary heating equipment
- 1.3 Auxiliaries solely related to heating
  - 1.3.1 Fans
  - 1.3.2 Pumps
  - 1.3.3 Burners
  - 1.3.4 Fuel Heating
- 1.4 Auxiliaries solely related to heat extraction
  - 1.4.1 Fans
  - 1.4.2 Pumps

2. Cooling
- 2.1 Initial or prime cooling equipment
- 2.2 Supplementary cooling equipment
- 2.3 Auxiliaries solely related to cooling supply
  - 2.3.1 Fans
  - 2.3.2 Pumps
- 2.4 Auxiliaries solely related to heat rejection
  - 2.4.1 Fans
  - 2.4.2 Pumps

3. Heating and/or Cooling
- 3.1 Initial or prime heating and/or cooling equipment
- 3.2 Supplementary heating and/or cooling equipment
- 3.3 Auxiliaries related to both heating and cooling
  - 3.3.1 Fans
  - 3.3.2 Pumps

4. Exhaust Fans

5. Hot and Cold Service Water

- 5.1 Initial or prime heating equipment
- 5.2 Supplementary heating equipment
- 5.3 Auxiliaries related to hot and cold service water
  - 5.3.1 Fans
  - 5.3.2 Pumps

6. Illumination
- 6.1 Indoor
  - 6.1.1 In conditioned space
  - 6.1.2 In nonconditioned space
- 6.2 Exterior

7. Refrigeration for Other than Comfort Cooling
8. Cooking
9. Vertical Transportation
10. Equipment Not Related to HVAC
11. Other
12. Building Description
- 12.1 Location
- 12.2 Type
- 12.3 Use
- 12.4 Size (conditioned floor area)

Figure 17. Functional uses of energy hierarchy from ANSI/ASHRAE Standard 105 [5].

5.3. Laboratories for the 21st Century Program [20, 21]

As part of the Laboratories for the 21st Century Program [20], an effort has been undertaken to "develop a standard set of energy performance metrics that will become commonly used in the design, commissioning, and operation of laboratories [21]." These metrics are intended to support both benchmarking and performance tracking over time, leading to continuous improvement of laboratory performance. It is envisioned that the resulting set of performance metrics will be used consistently within the various related activities of the Laboratories for the 21st Century Program.

This effort is focused on identifying a set of performance metrics that will quantify both the load required by a laboratory and the efficiency of the facility systems in meeting this load. The objective is to support comparison between different laboratories and between a given laboratory and both target and idealized performance metric values. A further objective is to provide the specification for a database that can be used to collect actual laboratory performance data and support laboratory benchmarking.

The performance metrics set that has been developed by participants in this effort are shown in Figure 18. These metrics have been reorganized here to maintain consistency with previously presented metric sets. The metrics have also been renamed to more fully express their meaning.

Whole Laboratory
- Whole Laboratory Annual Total Site EUI [Site Btu/ft^2-year]
- Whole Laboratory Annual Total Source EUI [Source Btu/ft^2-year]
- Whole Laboratory Annual Total Electric [kWh/ft^2-year]
- Whole Laboratory Annual Peak Electric [kW/ft^2-year]
- Whole Laboratory Annual Energy Cost [$/ft^2-year]
- Whole Laboratory Energy Effectiveness [Idealized Btu/Actual Btu * 100]

Heating System
- Heating Plant Annual EUI [Btu/ft^2-year]

Cooling System
- Cooling Plant Annual EUI [kWh/ft^2-year]
- Cooling Plant Average Efficiency [kW/ton]
- Cooling Plant Peak [W/ft^2]

Cooling Plant Peak Tons [tons/ft^2]
Cooling Plant Average Tons [tons/ft^2]

Lighting System
Lighting Annual EUI [kWh/ft^2-year]
Lighting Peak [W/ft^2]

Ventilation System
Ventilation Annual EUI [kWh/ft^2-year]
Ventilation Peak [W/cfm]
Ventilation Average [cfm/peak cfm]

Equipment
Process/Plug Annual EUI [kWh/ft^2-year]
Process/Plug Peak [W/ft^2]

Figure 18. Laboratory energy performance metrics from the Labs21 Program [21].

Similarly to the U.S. DOE High-Performance Buildings Metrics Project discussed above, this effort went on to identify additional data elements required for both calculating the metrics and filtering data records in the envisioned performance database. These data elements are shown in Figure 19. Note that not all of these data elements are simple quantities. In fact some are text-based descriptions of facility features and systems.

Building/Laboratory Description
Number of Buildings
Year Built
Building Gross Floor Area
Location Zip Code
Laboratory Net Floor Area (requiring 100% OA)
Laboratory Use (e.g. research, testing, teaching, or production)
Laboratory Type (e.g. biologic, chemical, physical)
Laboratory Category (e.g. wet 100% OA, dry recirc., or animal)
HVAC Type (check offs and narrative)
Cooling Plant Capacity (tons)
Efficiency Features (the “story” behind the performance including check offs and narrative)
Process Load Description
Indoor Design Conditions
Occupancy Hours
    Occupants
    Occupied Hours/Time

Energy
Annual Energy Utility Cost
Annual Heating BTUs (source)
Peak Cooling Tons
Average Cooling Tons
Peak CFM (sum of exhaust, supply, and recirculation fans)
Average Total CFM (sum of exhaust, supply, and recirculation fans)
Annual Peak kW and kWh (site)
    Total Building
    Ventilation
    Cooling Plant
    Lighting
    Process/Plug

Figure 19. Data elements required for metric calculation and database filtering [21].

5.4. Oakland Administration Buildings Performance Metrics [22]

It is one thing to define a set of performance metrics through group brainstorming and consensus discussion in the manner in which the above examples were developed. It is another thing to actually make use of these performance metric sets in a real-world building project. An ongoing case study of the Oakland Administration Buildings Performance Contract process has exposed a number of difficulties in tracking building performance from pre-design planning through design, construction, commissioning, and operations phases of a building project. To a large extent these difficulties have stemmed from the novelty of the performance contracting process and from problems in data collection and in calibrating simulation models to the many changes in data and modeling assumptions over time.

Yet to some degree the difficulties also resulted from inadequate information management methods that could be improved using the methods described in this report. In particular, a consistent definition of key performance metrics, not only at the whole-building level, but also at system and component levels, could substantially improve the overall process. A retrospective study of the collective data sets from the Oakland Administration Buildings project was undertaken as part of the same High Performance Commercial Building Systems Program of which this research is part. This study lead to the definition and application of a number of specific performance metrics for which values were calculated and compared across the life cycle of the building project. The details of this study are available elsewhere [22].

The performance metrics that were defined within the case study can be organized similarly to the above metric sets as shown in Figure 20. Values were calculated for each of these metrics at various stages of the building project based on simulations of the building design, and from over 500 monitored data points in the occupied building. Utility bill data were also analyzed in an attempt to crosscheck these values.

Whole Building
- Whole Building Annual Electricity Usage [MWh/year]
- Whole Building Annual Gas Usage [Therm/year]
- Whole Building Annual Energy Usage [MBtu/year]
- Whole Building Annual Energy Cost [$US/year]
- Whole Building Annual Energy Cost Intensity [$US/ft^2-year]
- Whole Building Monthly Energy Cost Intensity [$US/ft^2-month]
- Whole Building Annual Energy Use Intensity [kBtu/ft^2-year]

HVAC System
- Chiller Performance [kW/ton]
- HVAC System Annual Electricity EUI [kWh/ft^2-year]
- Heating System Annual Gas EUI [Therm/ft^2-year]

Lighting System
- Lighting Annual EUI [kWh/ft^2-year]

Equipment
- Plug Annual EUI [kWh/ft^2-year]
- Miscellaneous Equipment Annual EUI [kWh/ft^2-year]

Figure 20. Performance metrics from the Oakland Administration Buildings case study [22].

Additional data elements characterizing the building and local site weather were also collected. These data elements are shown in Figure 21 and are similar to those shown in Figure 16 and Figure 19 for previous metric sets. Again, these building characteristics would be contained within the Product Model portion of an IFC file as illustrated in Figure 3, while hourly weather data would most likely be archived in a separate data file referenced within the IFC file.

Building Characteristics
- Area
  - Gross Area [ft^2]
- Utility Rate

Electricity Rate Plan [category]
Gas Rate Plan [category]
Consumption [$US/unit]
Demand [$US/peak unit]
Schedule [?]
Ventilation System
Ventilation Design Rate [cfm/ft^2]
Equipment
Plug Load Density [W/ft^2]
Schedules
Occupancy Schedule [%(Persons/ft^2)/hour]
System Schedules [%(SystemOn)/hour]
Weather Characteristics
Outside Air Temperature
OAT [degreeF/hour]

Figure 21. Building and weather characteristics from the Oakland Administration Buildings study [22].

5.5. Instantiating Standardized Performance Metric Sets in Metracker

As discussed in Section 3.3.2, under the current Metracker implementation, Performance Objectives constitute the primary nodes within the Performance Model branches of a Metracker hierarchy. Multiple Performance Metrics can be associated with each Objective node as children of that node; however, Performance Metrics cannot themselves be nested hierarchically. This structure is illustrated in Figure 4.

Metracker has been developed to support alternative methods of instantiating these Performance Objective/Metric hierarchies within a given building project archive. Performance Objectives can be created individually at desired locations within a hierarchy. In this manner, whole branches of a hierarchy can be created manually from scratch. Alternatively, an entire hierarchy of Objectives and Metrics can be imported into a project from an existing IFC data file. An imported hierarchy can be added wholesale at any node within the project Performance Model.

This latter method of importing complete hierarchies provides the means of instantiating standardized performance metric sets in Metracker project data files. Each of the metric sets presented in this section could first be created manually and saved to separate IFC data files. Subsequently, a new building project that has standardized on one of these metric sets can import the selected set into a project version IFC data file as the starting point for that project's Performance Model.

Figure 5 shows a screen shot from Metracker displaying an example hierarchy of Performance Objectives and Performance Metrics similar to the energy performance metrics set from the Labs21 Program shown in Figure 18. The example project displayed in Figure 5 was created in the manner described here. A similar method could also be used to create the equivalent of the performance objective frameworks presented in Section 4 for importing into a Metracker project version.

5.6. A Comparison of the Standardized Performance Metric Sets

There is considerable overlap between the candidate performance metrics sets presented above. Yet there are also some interesting additions and omissions that appear in comparing these sets. Table 1 is an attempt to make these commonalities and differences more readily apparent. Also, the somewhat generalized superset of individual Performance Metrics listed in this table represents a more comprehensive set of metrics for standardization.

The left column of the matrix in Table 1 lists a superset of Performance Metrics from the Metric Sets presented above. The separate Metric Sets are listed in the top row of the matrix. Checkmarks in individual cells indicate which of the Performance Metrics are contained in each Metric Set. The units of measurement that are indicated for each metric are meant to be generic in the same manner as that used in Section 5.1. Additional comments included with the checkmarks in each column denote additions or restrictions related to the metric in that row. For example, "Site/Source/Cost" denotes that values for the given metric are calculated for each of these cases, while "Site" alone denotes that only that case is included in the metric set.

Performance Metrics (listed units are generic, Btu, kWh => energy, ft^2 => area, yr => time, etc.)	**Resource Consumption, Environmental Loading of Energy Use[17]**	**ANSI/ASHRAE Standard 105-1984 (RA 99) [5]**	**Laboratories for the 21st Century [20, 21]**	**Oakland Administration Buildings [22]**
Whole Facility				
Normalized Energy Use [by energy type] (kBtu/ft^2-yr, $/$ft^2$-yr)	✓ Site/Source/Cost		✓ Site/Source/Cost	✓ Site/Cost
Normalized Atmospheric Emissions [by emission type] (lbs of emissions/ft^2-yr, $/$ft^2$-yr)	✓ Site/Source/Cost			
Normalized Water Pollution [by end pollution element/impact] (ft^3/ft^2-yr, $/ft2-yr)	✓ Site/Source/Cost			
Peak Demand (Annual, Daily, and Design Peak) [by fuel type] (kBtu/hr-ft^2, $/ft2)	✓ Site/Source/Cost		✓ Site	
Energy Effectiveness (Idealized Btu / Actual Btu * 100)			✓ Site	
Total Energy Use [by energy type, and combined] (MBtu/yr, $/$ft^2$-yr)				✓ Site/Cost
End Use/System				
Normalized Heating Energy Use [by energy type] (kBtu/ft^2-yr, $/$ft^2$-yr)	✓ Site/Source/Cost		✓ Site	✓ Site
Heating Energy Use [by energy type] (kBtu/yr)		✓ Site		
Heating Peak Demand (Annual, Daily, and Design Peak) [by fuel type] (kBtu/hr-ft^2, $/ft2)	✓ Site/Source/Cost			
Normalized Cooling Energy Use [by energy type] (kBtu/ft^2-yr, $/$ft^2$-yr)	✓ Site/Source/Cost		✓ Site	
Cooling Energy Use [by energy type] (kBtu/yr)		✓ Site		
Cooling Peak Demand (Annual, Daily, and Design Peak) [by fuel type] (kBtu/hr-ft^2, $/ft2)	✓ Site/Source/Cost		✓ Site	

End Use/System (cont.)				
Cooling Peak Tons (Annual) (tons/ft^2)			✓ Site	
Cooling Average Tons (Annual) (tons/ft^2)			✓ Site	
Cooling Average Efficiency (kW/ton)	✓ Site		✓ Site	✓ Site Chiller
Normalized HVAC Electricity Use (kWh/ft^2-yr)				✓ Site
Normalized Lighting Energy Use [by energy type] (kBtu/ft^2-yr, \$/ft^2-yr)	✓ Site/Source/Cost		✓ Site	✓ Site
Lighting Energy Use [by energy type] (kBtu/yr)		✓ Site		
Lighting Peak (W/ft^2)			✓ Site	
Normalized Ventilation Energy Use [by energy type] (kBtu/ft^2-yr, \$/ft^2-yr)	✓ Site/Source/Cost		✓ Site	
Ventilation Peak (W/cfm)			✓ Site	
Ventilation Average (cfm/peak cfm)			✓ Site	
Normalized Process Loads Energy Use [by energy type] (kBtu/ft^2-yr, \$/ft^2-yr)	✓ Site/Source/Cost		✓ Site	
Process Loads Energy Use [by energy type] (kBtu/yr)		✓ Site Refrig/Cooking		
Normalized Disaggregated Process Loads Energy Use [by load type] (kBtu/ft^2-yr, \$/ft^2-yr)	✓ Site/Source/Cost			
Process/Plug Loads Peak (W/ft^2)			✓ Site	
Normalized Plug Loads Energy Use [by energy type] (kBtu/ft^2-yr, \$/ft^2-yr)	✓ Site/Source/Cost		✓ Site	✓ Site
Normalized Miscellaneous Equipment Energy Use [by energy type] (kWh/ft^2-yr)				✓ Site
Miscellaneous Equipment Energy Use [by energy type] (kWh/yr)		✓ Site		
Vertical Transportation Energy Use [by energy type] (kBtu/yr)		✓ Site		

End Use/System (cont.)				
Service Water Energy Use [by energy type] (kBtu/yr)		✓ Site		
Normalized Water Consumption [by end use] (ft^3/ft^2-yr, \$/ft2-yr)	✓ Site/Source/Cost			
Component/Equipment				
Cooling Equipment Efficiency [Design, not Actual Use] (kW/ton)	✓			
Cooling Equipment Sizing [Design, not Actual Use] ($tons/ft^2$)	✓			
Auxiliary Cooling Equipment Energy Use (Fans/Pumps) [by energy type] (kBtu/yr)		✓ Site		
Auxiliary Heating Equipment Energy Use (Fans/Pumps/Burners/Fuel Heating) [by energy type] (kBtu/yr)		✓ Site		
Lighting Equipment Efficiency [Design, not Actual Use] (fc/W)	✓			
Lighting Equipment Sizing [Design, not Actual Use] (W/ft^2)	✓			
Ventilation Equipment Efficiency [Design, not Actual Use] (W/cfm)	✓			
Ventilation Equipment Sizing [Design, not Actual Use] (cfm/ft^2)	✓			

Table 1. Comparative matrix of candidate standardized performance metric sets.

6. Related Work and Market Connections

The concepts underlying performance metrics and their application to tracking building performance span the entire life cycle of a building. There are a number of related efforts that potentially interact with the research described here at each stage of the life cycle. Describing these interactions serves not only to further illustrate various applications of these concepts, but also to identify potential avenues to making market connections for this research. These interactions are best discussed within the chronological context of life cycle activities.

Pre-design planning should ideally lead to a clear specification of the performance expectations for a new or to-be-renovated building. This process begins with identification of general qualitative performance objectives, but should then lead to quantitative performance metric benchmarks that will guide subsequent design and operation decisions.

The pre-design specification of expected performance is one application of statistics-based performance benchmarking techniques such as those developed in the Web-based Benchmarking

Task of this High Performance Commercial Building Systems Program [23] and in the Labs for the 21st Century Benchmarking Database Tool (BDT) [25]. Energy benchmarking tools like ARCH, Cal-ARCH, and the Labs21 BDT can be used to determine a benchmark whole-building EUI that would achieve the desired level of performance for a new building of a given type in a given location, relative to the existing building stock (e.g., a 75th percentile ranking).

Pre-design planning specification of performance benchmarks is also an application of the proposed BSR/ASHRAE/IESNA Addendum e to ANSI/ASHRAE/IESNA Standard 90.1-2001 [19]. The modeling procedure defined in this addendum leads to simulation-based benchmark values not only for the envisioned whole-building Design Energy Cost (DEC), but also for all key energy-related performance metrics defined in the standard metric sets identified in Section 5 above. Furthermore, the complete building model developed to simulate the DEC can be archived using the extended IFC data model illustrated in Figure 3, which would serve to document the myriad assumptions behind the generated metric benchmark values.

The work to extend the IFC schemata to support the modeling and simulation of HVAC components and systems also comes into play in the above scenario. This is the work being done in the Interoperability Task of the High Performance Commercial Building Systems Program [24]. In particular, the IFCs in EnergyPlus Task is implementing methods of exchanging both the required input for EnergyPlus and its generated output with IFC data files. These methods could support the IFC-based archival (and subsequent interoperable sharing) of metric values calculated by simulation.

The capabilities discussed in the previous two paragraphs proffer market connections for this research through interaction with ongoing efforts of the USGBC, ASHRAE, and the U.S. DOE. The USGBC connection would be through providing tools and techniques that support the LEED rating process [14]. The ASHRAE connection would be through applying the 90.1 Addendum e procedures [19] to LEED. The U.S. DOE connections would be through helping create a market niche for EnergyPlus and energy performance metric tracking within the LEED process and the High-Performance Building Metrics Project [15]. Each of these connections would increase the visibility of the research reported here by illustrating the application of the performance metric concepts to these activities.

The ability to archive and share the combination of metric data and the building model that was used to calculate these data has application downstream of the design phase as well. This constitutes the type of clear and quantitative documentation of design intent envisioned by tools such as the LBNL Applications Team (A-Team) Design Intent Tool [26]. This is crucial documentation for participants in activities such as those identified by the Integrated Commissioning and Diagnostics Element of the High Performance Commercial Building Systems Program [27].

Lastly, the process of retrofitting buildings is similar in many ways to the process of designing and constructing new buildings. The use of simulation-based retrofit tools such as RESEM-CA [28] could therefore be supported in the same manner as that described for EnergyPlus above. Archiving both the input to and output from RESEM-CA in the extended IFC model developed within this research would allow these data to be shared across the remainder of the building life cycle.

7. Acknowledgements

This work is supported by the California Energy Commission, Public Interest Energy Research Program, under Contract No. 400-99-012. This work has also been supported by the US Environmental Protection Agency, Climate Protection Division, and the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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